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A Single Electron Transistor (SET) turns on and off for an electron added to it. Our goal is to better control and understands the physics of SETs in order to make them technologically useful. Our work has shown that the SET behaves like an artificial atom, in that the number of electrons and the energy are both quantized. The goal of our current project is to measure the electron spin resonance in this artificial atom, when it contains an odd number of electrons. This is an important step in exploring whether one could use SET's for quantum computing.

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FINAL Progress Report

One important result of our research is published in Kogan *et al*[i] The single-electron transistor (SET) we have studied is similar to those used by Goldhaber-Gordon *et al.* It is created by imposing an external potential on a 2DEG at the interface of a GaAs/AlAs heterostructure. The heterostructure we have used has the 2DEG closer to the GaAs/AlAs interface and therefore makes smaller quantum dots than usual. We create the confining potential with electrodes shown in Fig. 1a. Applying a negative voltage to the three confining electrodes (tl, bl and r in Fig. 1a) depletes the 2DEG underneath them and forms two tunnel barriers separating a droplet of electrons from the 2DEG regions on either side, which act as the source and drain leads. The confinement caused by the electrodes is supplemented by shallow etching of the cap layer before the gate electrodes are deposited. We estimate that our droplet is about 100 nm in diameter and contains about 50 electrons.

Figure 1b shows the differential conductance of our SET for a range of plunger gate (g in Fig. 1a) voltage $\Delta V_g = V_g - V_0$, over which two electrons are added to the quantum dot. The broad bands forming a pair of diamonds result from the threshold for charge fluctuations induced by the drain-source voltage V_{ds} and V_g. The sharp feature at $V_{ds} = 0$, present for 10 mV< ΔV_g < 40mV, is identified as the Kondo peak for odd N. Thus, the unusual features in the adjacent diamonds are associated with even N.

In the left-hand diamond of Fig. 1b, we see, at the far left, two sharp peaks positioned symmetrically around V_{ds} =0. As ΔV_g is increased the two peaks move together, until they merge to form a zero-bias peak. After remaining at zero bias for a range of ΔV_g the two peaks separate again. Although we do not generally observe such symmetric patterns, we find similar behavior for most even N: sharp peaks that shift with gate voltage at a rate such that the splitting disappears over ~10 mV. When the splitting vanishes, a zero-bias Kondo peak results and remains at zero bias as ΔV_g is changed further.

We assume that when there is no zero-bias Kondo peak the ground state is the singlet and that, the weak peaks observed symmetrically around V_{ds}=0 result from Kondo screening of the excited-state triplet. We further assume that the shift of the peaks with gate voltage results from the change of energy separation of the lowest excited state from the ground state. That is, while all levels shift in energy at approximately the same rate because of the average electrostatic potential change caused by the gate, the transverse electric field, caused by the voltages between the plunger gate and the confining gates, affects each level of the artificial atom differently.

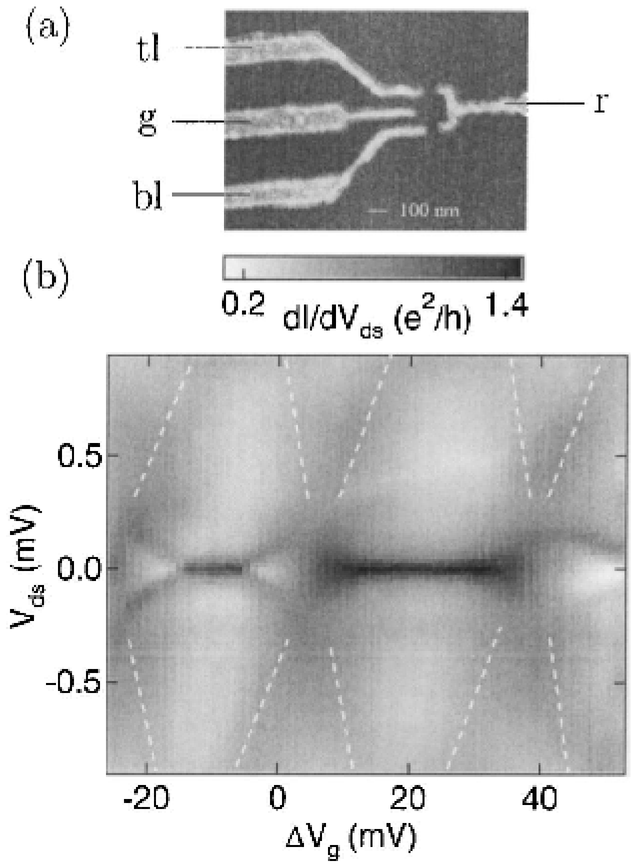

Figure 1: (a) Electron micrograph of a device nominally identical to that used in this experiment. (b) Differential conductance as a function of gate and drain-source voltage. The top left (tl) bottom left (bl) and right (r) electrodes confine the electrons. The dashed white lines are included as guides to the eye to locate the Coulomb-blockade diamonds. The high conductance ridge at V_{ds}=0 is characteristic of the Kondo effect for S=1/2, so the diamonds on either side correspond to even numbers of electrons. The voltages on the rightmost, top left, and bottom left electrodes in (a) are varied to give different behavior in the odd-electron diamonds, left and (partially visible) far right.

Hofstetter and Schoeller[ii] have calculated the evolution of the differential conductance for an SET with two single-channel leads and two orbitals, as a function of the level spacing. Their Hamiltonian includes, for the excited state, a Heisenberg exchange interaction. These authors predict that, when the level spacing is larger than J/4, where J is the exchange interaction, two peaks should be seen in the differential conductance, displaced symmetrically from zero bias by the energy of the excited-state triplet relative to the singlet ground state. When the triplet becomes the ground state a zero-bias Kondo peak is predicted. This is consistent with what we observe.

However, one would expect some coupling between the two orbitals that would cause them to avoid crossing. Were the coupling small enough, the triplet would become the ground state near the anti-crossing. However, for larger coupling the singlet would remain the ground state. The first type of behavior is seen in Figure 1 and the second in Figure 2.

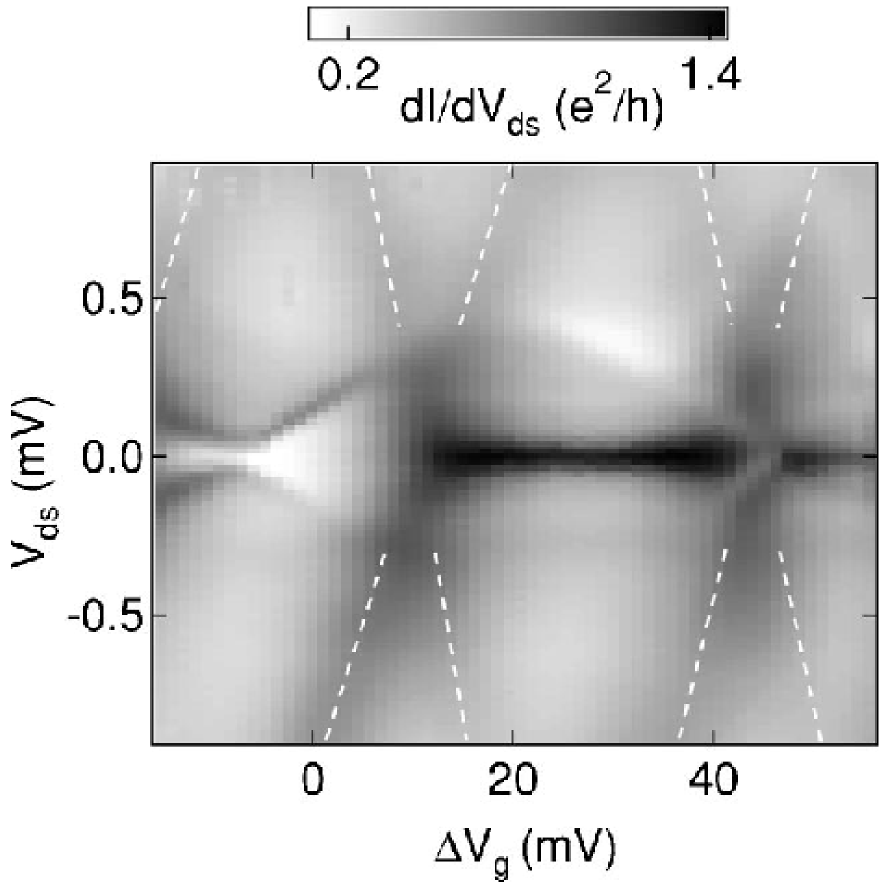

Figure 2. Differential conductance as a function of drain-source voltage and gate voltage. The confining electrodes (see Fig.1) have been changed to increase the splitting between the triplet and singlet in the diamond at the left. This allows one to see the entire anti-crossing of the two levels.

We have devices with the same gate structure on two different heterostructures. We believe that, because of differences in the depth of the 2DEG, one set of dots is somewhat larger than the other. The larger dots show triplet ground states, whereas the smaller ones do not. As found by Schmidt *et al.*,**Error! Bookmark not defined.** still larger dots show triplet Kondo for almost all even N. Using dots of the right size, we are therefore able to drive the dot through the singlet-triplet transition *at zero magnetic field.*

A major effort during the past three years has been to reduce the effective electron temperature of our SETs. For most low-temperature transport experiments, it is not possible to directly measure electron temperatures. One generally finds that the property being measured, conductance for example, saturates as the lattice temperature is lowered, and one assumes that the electron temperature is then higher than that of the lattice. However, because the line-shape of the Coulomb charging peaks in conductance reflects the Fermi-Dirac distribution function, one can measure the electron temperature directly. Using this measure, we and other groups have found that electron temperatures appear to saturate below about 50mK, even when the lattice temperature is much lower.

In order to attain lower electron temperatures we designed a refrigerator with filtering to eliminate high frequency pickup and noise, and we built a measuring system that is entirely analog and requires no ac power in our screened room. We were surprised to find, after the system's completion, that the electron temperature was still ~100mK.

Believing that this elevated temperature is the result of pickup of electromagnetic excitation by our high-impedence SET, we have taken all possible steps to exclude pickup from the device. This is challenging because to ensure that the SET is in equilibrium, we must ensure that all voltages between its leads are less than kT/e, which is of the order of microvolts at our lowest temperatures.

We believe that filtering and exclusion of digital electronics from the screened room eliminates high frequency pickup, so we have focused on low frequencies. Elimination of capacitive pickup, by careful shielding, and inductive pickup, by using twisted cables, typically gives a circuit with a no more than 10-20 microvolts rms of pickup. Mechanical vibrations in cables produce voltages because of piezo-electric effects in the dielectric. We reduce these by anchoring all cables carefully

The most demanding aspect of removing pickup is the careful elimination of the ground loops resulting from small currents in the grounded metal that provides shielding for the circuit. In part, such current results from the shielding action itself, in the metal walls for the room, for example. But it can also result from large currents being sunk through the lab ground by high-power equipment, such as electric motors, generators or power supplies. Because our SETs are so sensitive to small voltages, this is especially demanding. For example, a very small current of 10 milliamps in a ground wire of only a milli-ohm resistance included in our measuring circuit will perturb our measurement. The usual procedure of ensuring that the measurement circuit is grounded in one and only one place is successful if followed scrupulously with very short, high conductance leads.

Following these procedures, we are able to bring the noise level in our circuits below the level of the input noise of our detection instrument, the Ithaco 1211 current amplifier, which is 2-3 microvolts rms, or about 7-10 microvolts peak to peak. After this careful work our analysis of the temperature dependence of Coulomb charging peaks and Kondo peaks in differential conductance indicates that the electron temperature is now no higher than about 20mK.

We have observed photon sidebands of the Kondo peak in differential conductance. Shortly after the discovery of the Kondo effect in SETs theorists Goldin and Avishai[iii] predicted that in the presence of microwave electric fields, the Kondo peak would develop sidebands. However, Kaminski *et al.*[iv] have proposed that decoherence effects from the microwave excitation might be so drastic that the Kondo peak would disappear without the emergence of sidebands.

Elzerman *et al.*[v] observed the suppression of the zero bias Kondo peak, but no one has ever observed the sidebands. In late 2003 we succeeded in doing this.

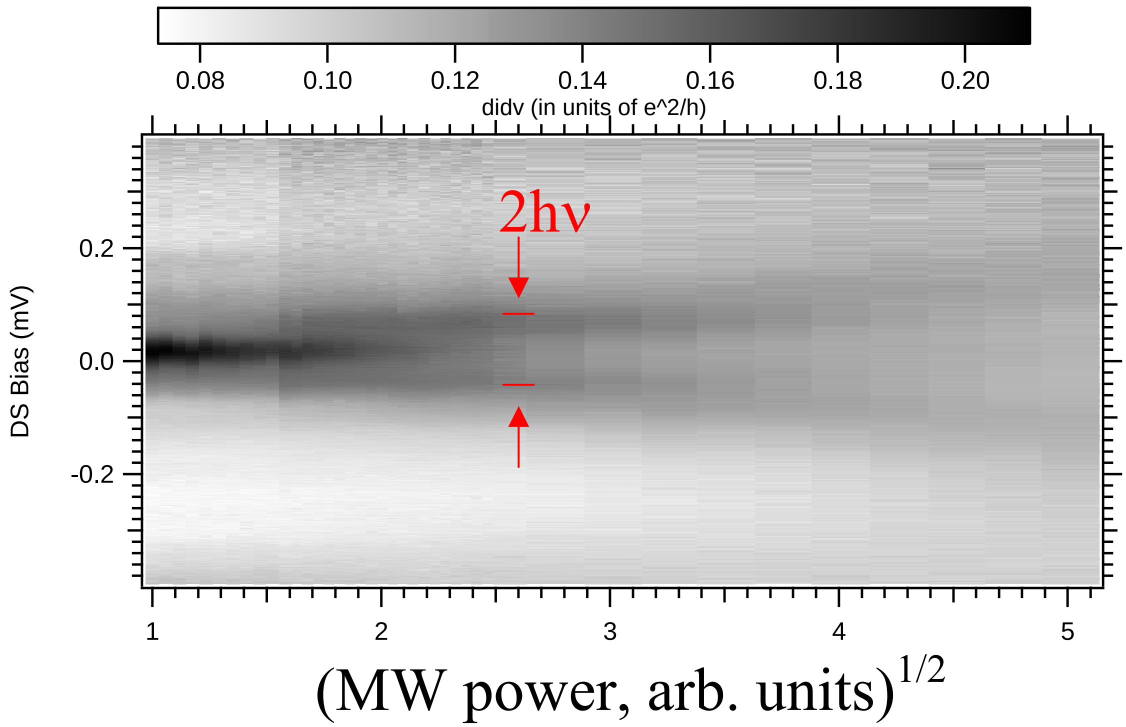

Figure 3. Differential conductance as a function of microwave voltage between source and drain electrodes. Photon sidebands are observed just before zero bias peak is suppressed.

Figure 3 shows the differential conductance on a gray scale as a function of the microwave voltage falling across the quantum dot. When the microwave voltage becomes of the order of $\hbar\omega/e$ one sees that the central Kondo peak is reduced in size and the photon sidebands emerge. Multiple photon sidebands are not seen. This may be the result of heating by the microwaves. To illustrate that these are indeed photon sidebands we plot the splitting between the two peaks as a function of the microwave voltage in Figure 4.

Our cavity acts as a filter, reflecting noise from the microwave generator that is not at the resonant frequency. This may help us to observe the sidebands. In addition, the small size of our quantum dots makes the orbital level spacing larger than the microwave energy. This may make the photon sidebands of the Kondo peak easier to observe.

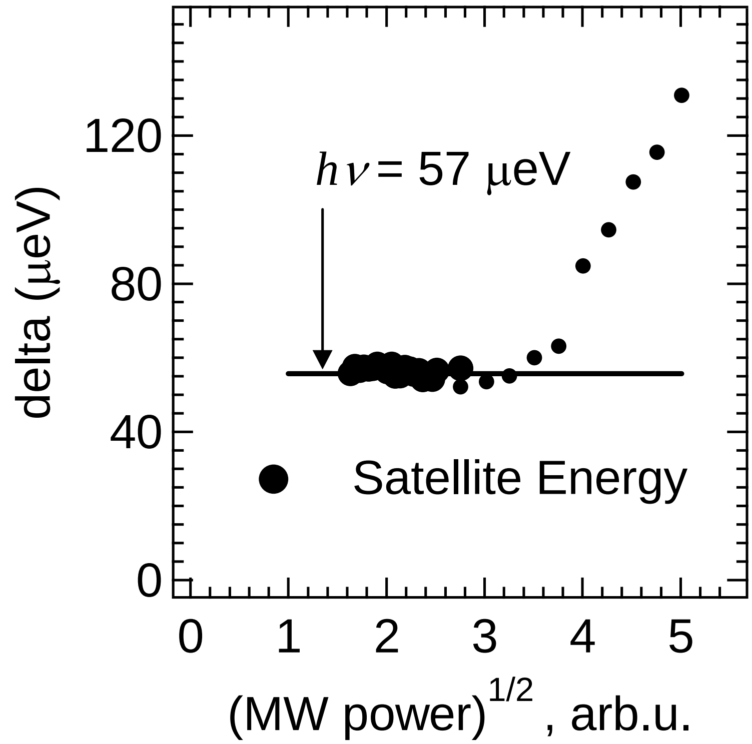

Figure 4. DC voltage at which the differential conductance is maximum (excluding the zero-bias peak). At high microwave voltages the peak occurs approximately where the DC and microwave voltages are equal. However, at low microwave excitation, the peak occurs where the voltage equals hν/e, where ν is the microwave frequency.

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Honors
David Goldhaber-Gordon was the first recipient of the George E. Valley Prize of the American Physical Society for work done as a graduate student in Marc Kastner's group at MIT.

Report of inventions
None